New physics in B_s mixing: Uplifted SUSY

Adam Martin (Fermilab)

based on work with B. Dobrescu and P. Fox (1005.4238)

Santa Fe Workshop, 2010

July 8th, 2010

Motivation

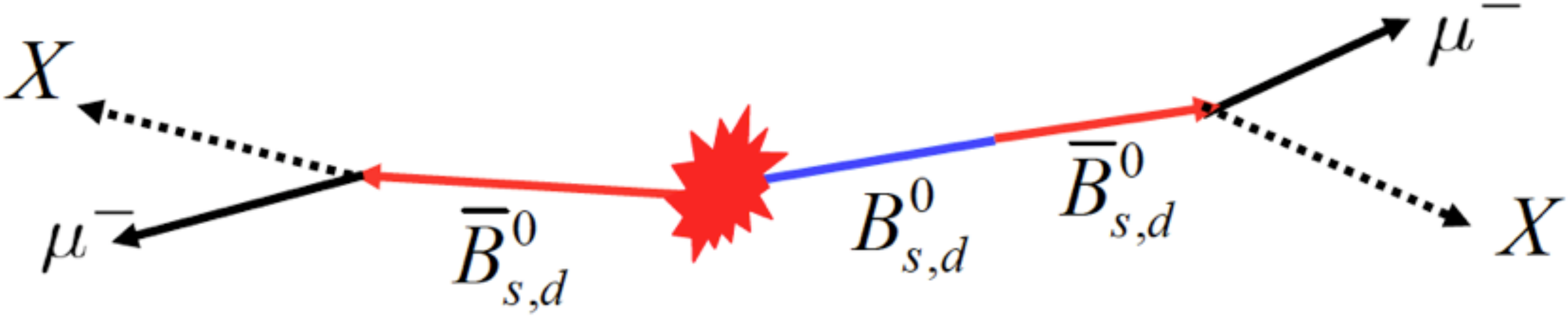
- D0 sees a ~1% asymmetry in the number of $\mu^-\mu^-$ vs. the number of $\mu^+\mu^+$

(1005.2757)

$$A^b_{SL} = -(9.57 \pm 2.51 \pm 1.46) \times 10^{-3}$$

3.2σ deviation from SM

- like-sign leptons are attributed to B^0_s and B^0_d oscillation



Outline

- B mixing in the SM
- adding new physics: where? how big?
- one approach: new contributions to the phase of M^s_{12}
- Uplifted SUSY as an example

Interpreting the D0 result

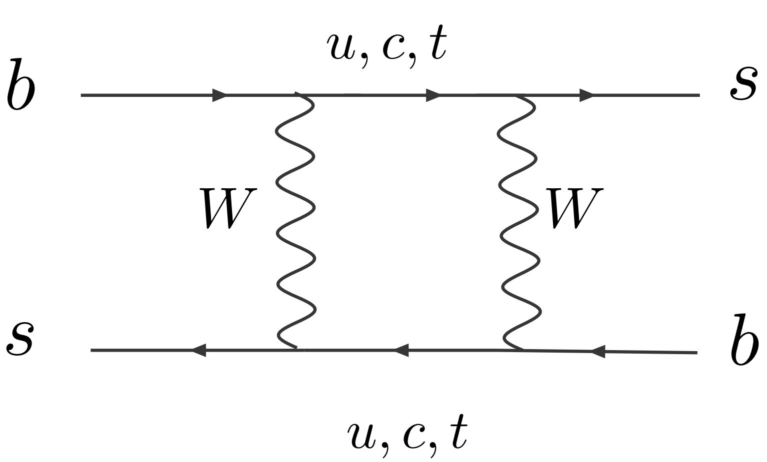
- B_s/B_d oscillation basics

$$B_q^0 = (\bar{b}q), \overline{B^0}_q = (\bar{q}b)$$

$$i\frac{d}{dt}\begin{pmatrix} B_q^0 \\ \overline{B^0}_q \end{pmatrix} = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}\begin{pmatrix} B_q^0 \\ \overline{B^0}_q \end{pmatrix}$$

all of the physics is in $M_{12} - \dfrac{i}{2}\Gamma_{12}$:

in the SM:



M_{12} vs. Γ_{12}

dispersive part

absorptive part (intermediate states go on-shell)

both complex, due to complex V_{CKM} couplings

Interpreting the D0 result

- dimuon asymmetry can be recast in terms of the B_s, B_d "wrong charge" semileptonic asymmetries

$$A^b_{SL} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = \frac{N^+_{RS}N^+_{WS} - N^-_{RS}N^+_{WS}}{N^+_{RS}N^+_{WS} + N^-_{RS}N^+_{WS}} \cong 0.5\ a^d_{SL} + 0.5\ a^s_{SL}$$

depend on what fraction of produced b go to B_s, B_d

where:

$$a^q_{SL} = \frac{N(\overline{B^0}_{phys} \to \ell^+ X) - N(B^0_{phys} \to \ell^- X)}{N(\overline{B^0}_{phys} \to \ell^+ X) + N(B^0_{phys} \to \ell^- X)} \simeq -\frac{|\Gamma^q_{12}|}{|M^q_{12}|} \sin(\phi^q_M - \phi^q_\Gamma) + \mathcal{O}(|\Gamma^q_{12}|^2)$$

some related quantities

$$a^q_{SL} = -\frac{|\Gamma_{12}|}{|M_{12}|} \sin(\phi_M - \phi_\Gamma), \quad \Delta M_s = 2|M_{12}|, \quad \Delta\Gamma = 2|\Gamma_{12}| \cos(\phi_M - \phi_\Gamma)$$

mass difference

lifetime difference

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depend on what fraction of produced b go to B_s, B_d

assumes $\mathcal{A}(b \to \ell^+ X), \mathcal{A}(\bar{b} \to \ell^- X) = 0$

where:

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mass difference

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In the Standard Model

- For now let's assume $a^d_{SL} = 0$ since the B_d system is tightly constrained by B-factories. Whole asymmetry comes from B_s

from expt.

$$(a^s_{SL})_{comb} \approx -(12.7 \pm 5.0) \times 10^{-3}$$

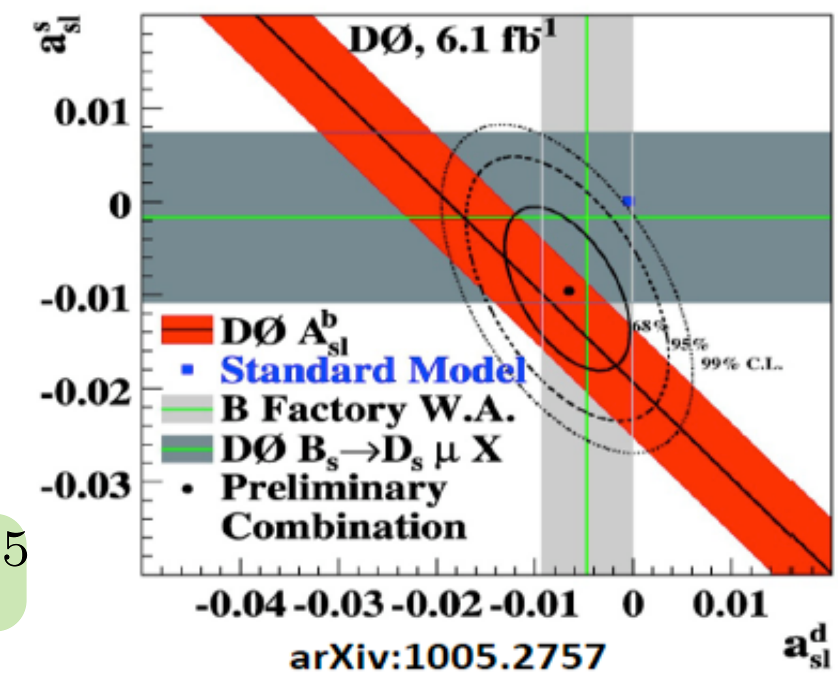
(D0 + older CDF, D0 results)

$$|M^{SM}_{12}| \simeq (9.0 \pm 1.4)\text{ps}^{-1}$$

$$|\Gamma^{SM}_{12}| = 0.045 \pm 0.012 \text{ ps}^{-1}$$

$$\sin(\phi_M - \phi_\Gamma)_{SM} \simeq (4.2 \pm 1.4) \times 10^{-3}$$

$$a^s_{SL}(SM) = (2.2 \pm 0.6) \times 10^{-5}$$



arXiv:1005.2757

New Physics in a^d_{SL}, a^s_{SL}

so, how do you get a bigger asymmetry in B_s?

$$a^s_{SL} = -\frac{|\Gamma_{12}|}{|M_{12}|}\sin\left(\phi_M - \phi_\Gamma\right)$$

- Decrease $|M_{12}|$: look easy in that SM is a loop process, but

$\Delta M_s = 2|M_{12}|$ is well measured, $\Delta M_s = 17.78 \pm 0.12 \text{ ps}^{-1}$

SM value $2|M_{12}^{SM}|$ is close to the experimental value, has small O(10%) theoretical uncertainty

not enough room here

New Physics in a^d_{SL}, a^s_{SL}

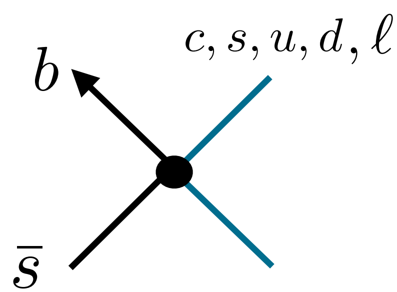
how do you get a bigger asymmetry?

$$a^s_{SL} = -\frac{|\Gamma_{12}|}{|M_{12}|}\sin(\phi_M - \phi_\Gamma)$$

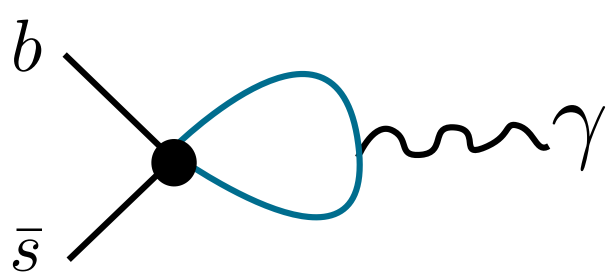
- Increase Γ_{12}: looks promising as not directly measured

$$\left(\Delta\Gamma = 2|\Gamma_{12}|\cos(\phi_M - \phi_\Gamma)\right)$$

introduce NP which connects $\bar{b}s$ to light SM fields



- BUT, any NP which contributes to also Γ_{12} contributes to Γ_i, M_{12}
- Also, new physics here must involve light particles in loops, so need to be careful about $b \to s\gamma$, etc.



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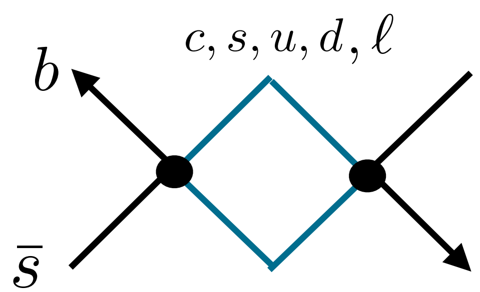

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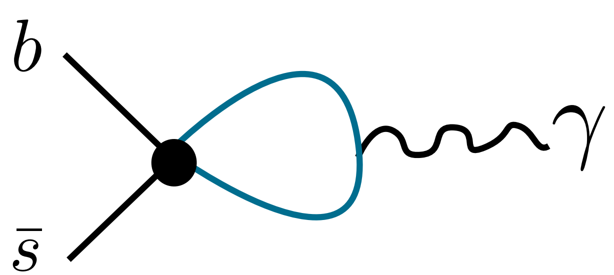
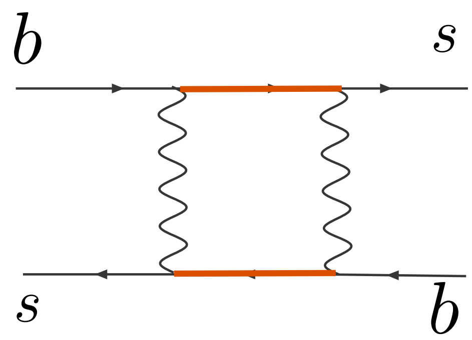


New Physics in a^d_{SL}, a^s_{SL}

more on Γ_{12}

Γ_{12}^{SM} = Im $\Big\{$



$\Big\}$

confusing, but rearrange slightly

$V_{KM} \to V_{KM}^*$

New Physics in a^d_{SL}, a^s_{SL}

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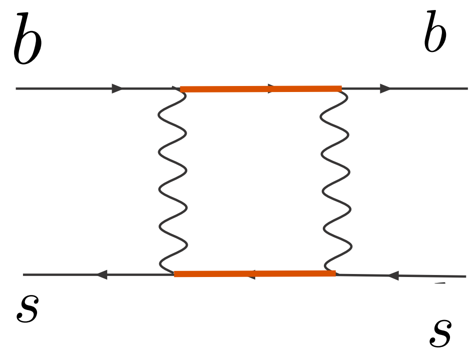
Γ_{12}^{SM} = Im $\Bigg\{$  $\Bigg\}$

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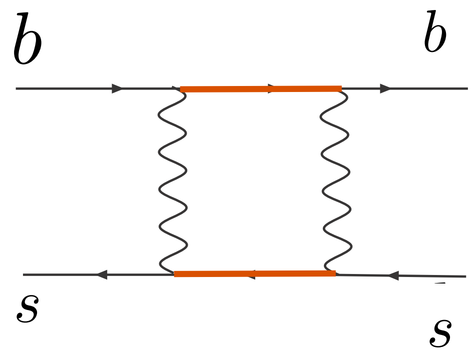

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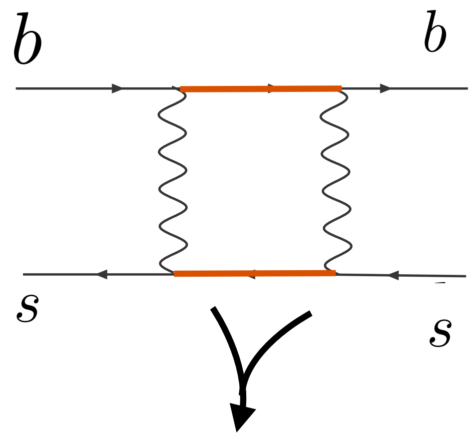

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confusing, but rearrange slightly

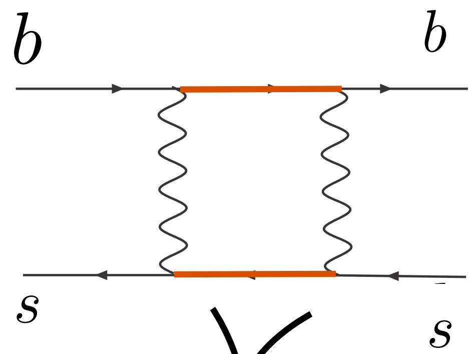
$V_{KM} \to V^*_{KM}$

$\Gamma_{\overline{B}\to XX}$

New Physics in a^d_{SL}, a^s_{SL}

more on Γ_{12}

Im



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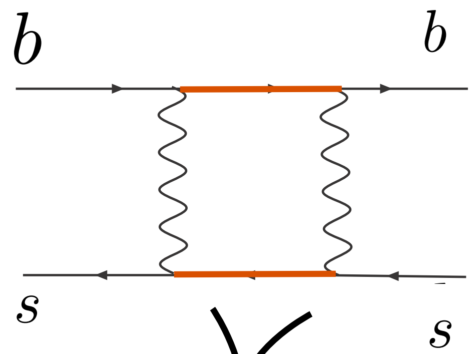
$V_{KM} \to V^*_{KM}$

so $\Gamma^{SM}_{12} \sim \Gamma_{\overline{B}\to XX} \sim \dfrac{G_F^2 f_B^2 M_B^3}{16\pi}$ from tree-level calculations

New Physics in a^d_{SL}, a^s_{SL}

more on Γ_{12}

Im $\Bigg\{$ 

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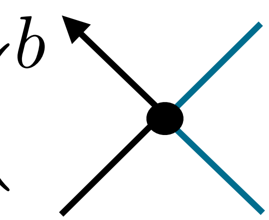
so new physics in Γ_{12} has to be large

$\dfrac{1}{\Lambda^2}\Bigg($ 

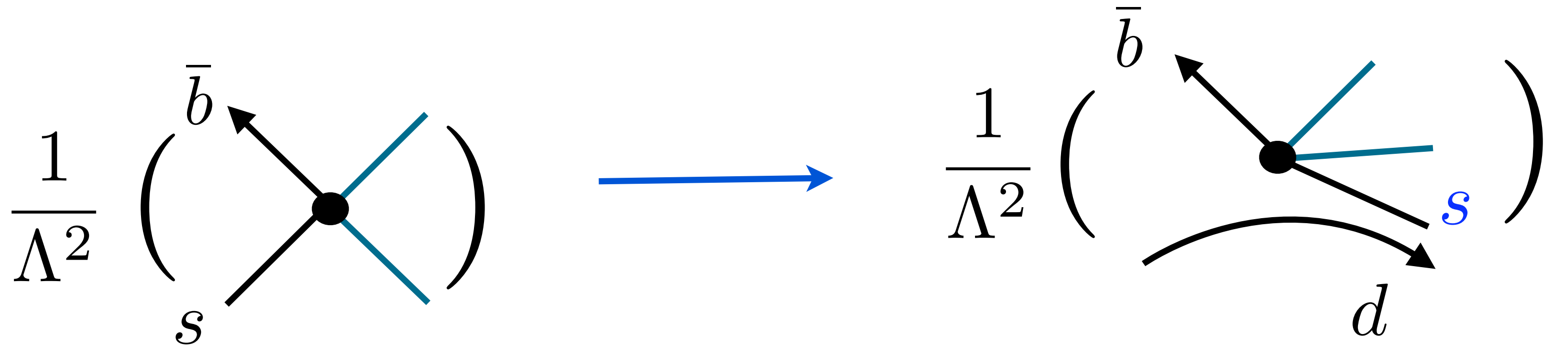
$\Bigg) \sim \dfrac{f_B^2 M_B^3}{16\pi\Lambda^2}$ $\longrightarrow$ big effects in $\Gamma_{B_s\to XX}$ and total width Γ_{B_s}

which are well measured

New Physics in a^d_{SL}, a^s_{SL}

more on Γ_{12}

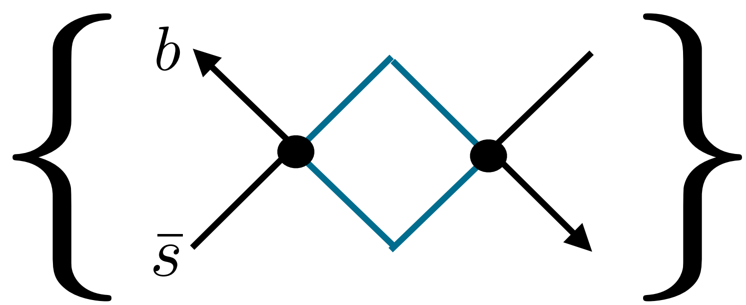
B$_d$ decays are also affected...



(see Bauer, Dunn 1006.1629)

as is M$_{12}$:

M_{12} = Re



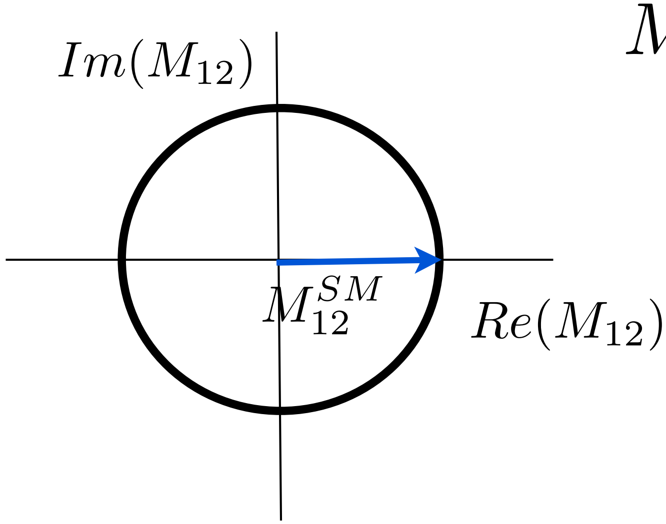
(almost) no room here!

New Physics in a^d_{SL}, a^s_{SL}

how do you get a bigger asymmetry?

$$a^s_{SL} = -\frac{|\Gamma_{12}|}{|M_{12}|}\sin\left(\phi_M - \phi_\Gamma\right)$$

- Increase the phase: phase in SM is small $\mathcal{O}(10^{-3})$
- based on previous arguments, changing the phase through new physics in mixing (M_{12}) seems easier



$$M_{12} = M_{12}^{SM} + |M_{12}^{NP}|e^{i\phi_{NP}}$$

What about $S_{\psi\Phi}$ (CPV in B $J/\psi\Phi$) ?

- different observable:

assuming one decay amplitude,
0^{th} order in Γ_{12}

$$\frac{N(\overline{B^0}_{phys} \to J/\psi\phi) - N(B^0_{phys} \to J/\psi\phi)}{N(\overline{B^0}_{phys} \to J/\psi\phi) + N(B^0_{phys} \to J/\psi\phi)} = -\sin(\Delta m t)\,\overbrace{\sin(\phi_M + 2\phi_f)}^{S_{\psi\Phi}}$$

CKM phase of tree-level $b \to c\bar{c}\bar{s}$ process

strictly speaking, not the same phase as in a^s_{SL}
(relative phase of M_{12} and Γ_{12})

in the SM: $\sin(\phi_M - \phi_\Gamma), \sin(\phi_M + 2\phi_f) \simeq 0$

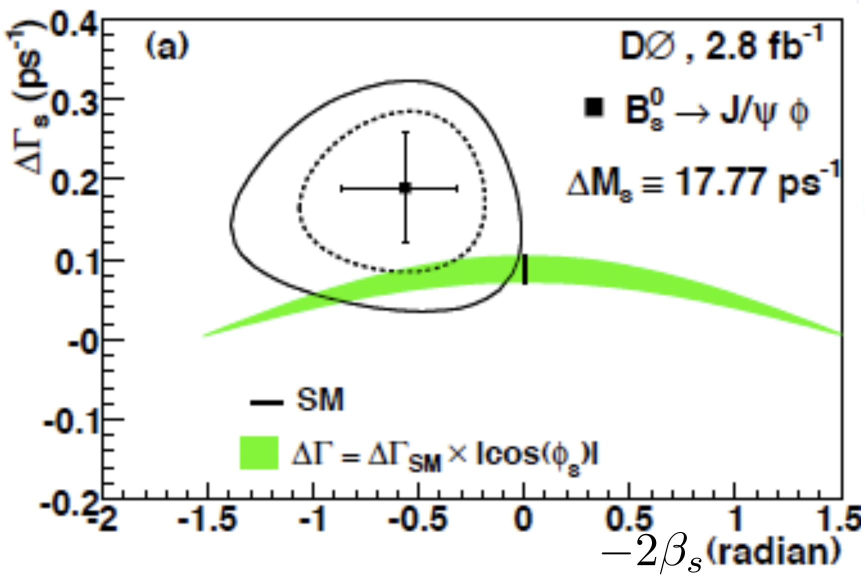
if NP only changes phase in mixing, effect will show up in both

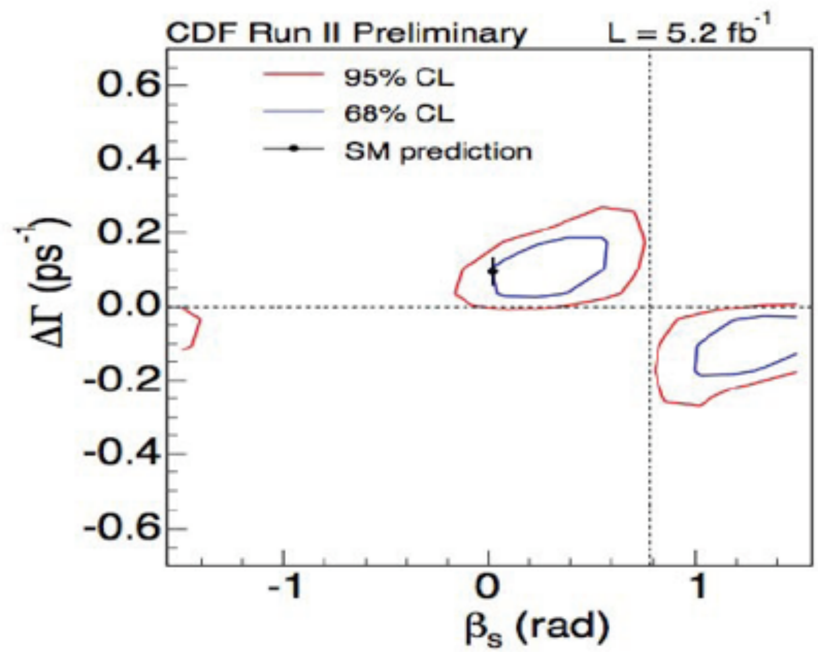
$$\sin(\phi_{NP} + \phi_M - \phi_\Gamma) \simeq \sin(\phi_{NP}) \simeq \sin(\phi_{NP} + \phi_M + 2\phi_f)$$

not the case if there is new physics in the phase of Γ_{12}

What about $S_{\psi\phi}$?

both CDF/D0 measure $S_{\psi\phi}$: extract $\Delta\Gamma$ and $\phi_M + 2\phi_f$





$$-2\beta_s \equiv \phi_M + 2\phi_f \approx \phi_M - \phi_\Gamma$$

- both experiments favor phases >> SM

- $\Delta\Gamma = 2|\Gamma_{12}|\cos(\phi_M - \phi_\Gamma)$ so if new physics only changes the phase, $|\Delta\Gamma|$ can only be smaller than $\Delta\Gamma^{SM} \cong 2|\Gamma_{12}^{SM}|$

a first approach

Based on what we've learned, changing the phase of M_{12} through new physics is a simple thing to try first

$$\Gamma_{12} = \Gamma_{12}^{SM} \qquad M_{12} = M_{12}^{NP} + M_{12}^{SM} \equiv C_{B_s} e^{i\phi_s} |M_{12}^{SM}|$$

(set phase in $M_{12}^{SM}, \Gamma_{12}^{SM}$ to zero)

$$a_{SL}^s = -\frac{|\Gamma_{12}^{SM}|}{|M_{12}^{SM}|} \frac{\sin\phi_s}{|C_{B_s}|}$$

plug in $M_{12}^{SM}, \Gamma_{12}^{SM}$, fit to a_{SL}^s and $\Delta M_s = 2|M_{12}| = 2|M_{12}^{SM}| C_{B_s}$

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$$\boxed{C_{B_s} = 0.98 \pm 0.15} \quad , \quad \boxed{\sin\phi_s = -2.5 \pm 1.3}$$

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Huh?

with the set of assumptions we've made and the current experimental central value, we find an unphysical scenario

So..

- central value will decrease once errors are reduced

Or.. we need to modify our theory assumptions

- new physics also in B_d (not clear how much it can help...)
- new physics in Γ_{12}^s (input from $S_{\psi\phi}$)
- not a simple 2 state mixing (ask Yang...)
- muons come from some other new physics (rate ~10^{-5} σ_b ?)
- others?

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- others?

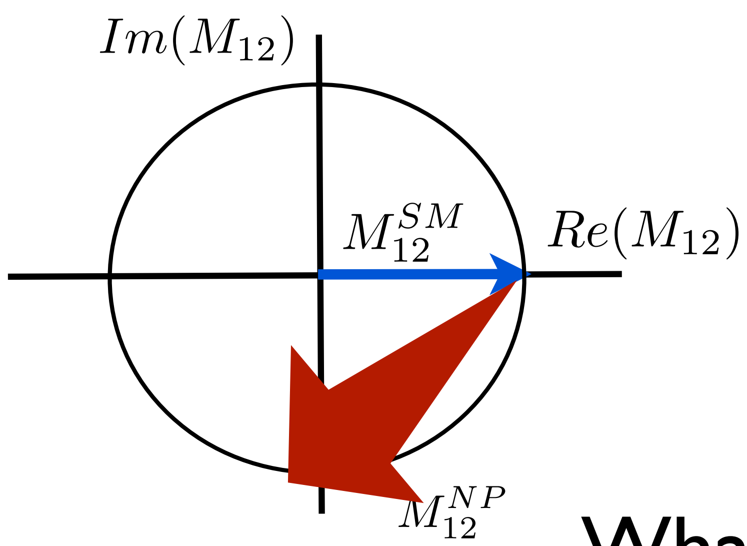
let's keep going with our current strategy

thinking outside the box

Consider the situation where $\sin\phi_s$ settles to a large, but physical value

$$\sin\phi_s \sim -1$$

In this case new physics of this form needs to be large and have a large phase



$$\frac{M_{12}^{NP}}{M_{12}^{SM}} = (C_{B_s} e^{i\phi_s} - 1)$$

$$\frac{|M_{12}^{NP}|}{|M_{12}^{SM}|} \sim \sqrt{2} \qquad arg(M_{12}^{NP}) \sim -3\pi/4$$

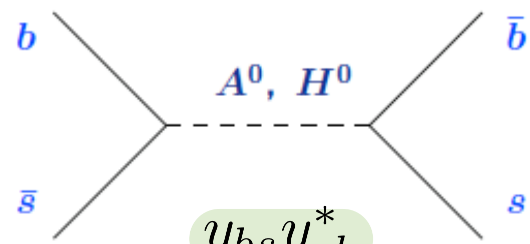
What new physics can generate this?

thinking outside the box

what about tree level scalar exchange:

... occurs in general two Higgs doublet models (THDM)

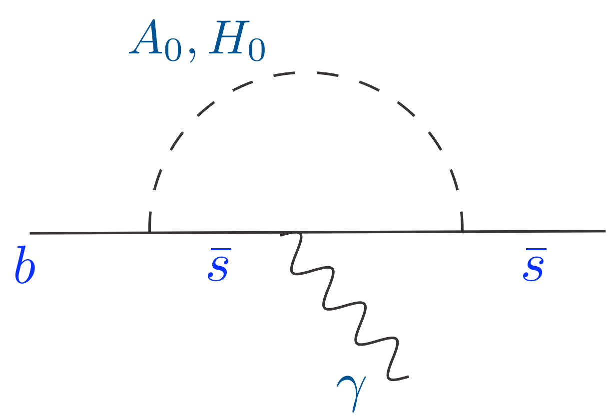
(up-, down-type quarks couple to both Higgses)



$\sim \frac{y_{bs} y_{sb}^*}{M_A^2}$ complex

$\Delta B = 2$ at tree level, while $\Delta B = 1$

only occurs at loop level -> parametrically smaller



thinking outside the `box'

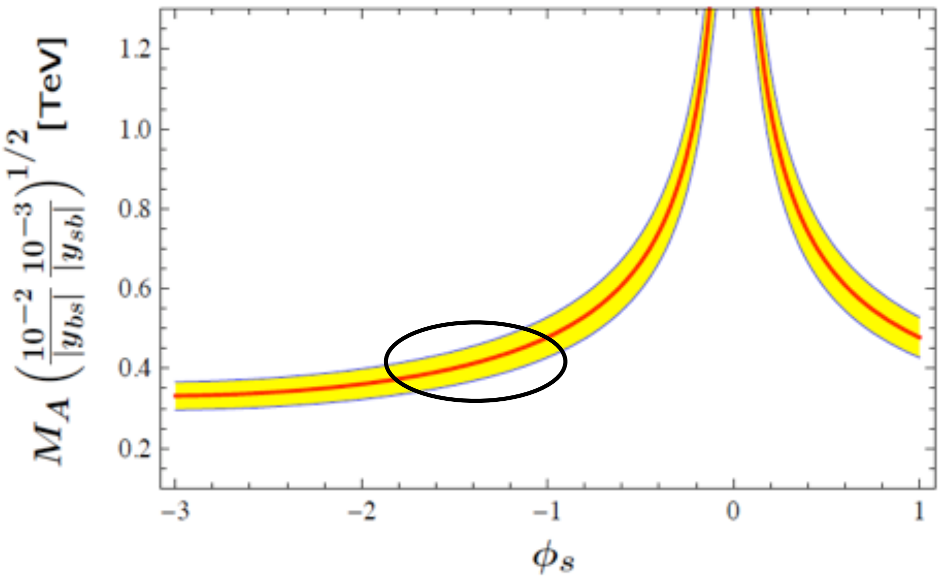
Get the right size effect for

$$M_A \sim 500 \text{ GeV}$$

$$y_{bs} \sim 0.01, |y_{sb}| \sim 0.001$$

'CKM sized'

>> than expected from
Higgs-related FCNC



but how do you get large enough $y_{bs}y^*_{sb}/M_A^2$ without screwing up other flavor observables?

From where? Uplifted SUSY

the MSSM is a two-Higgs doublet model

Holomorphy constrains the superpotential

$\longrightarrow$ when SUSY is preserved, `type-2' THDM

$$\mathcal{L} \supset -y_u u^c H_u Q_L - y_d d^c H_d Q_L$$

BUT, once SUSY is broken, integrate out superpartners

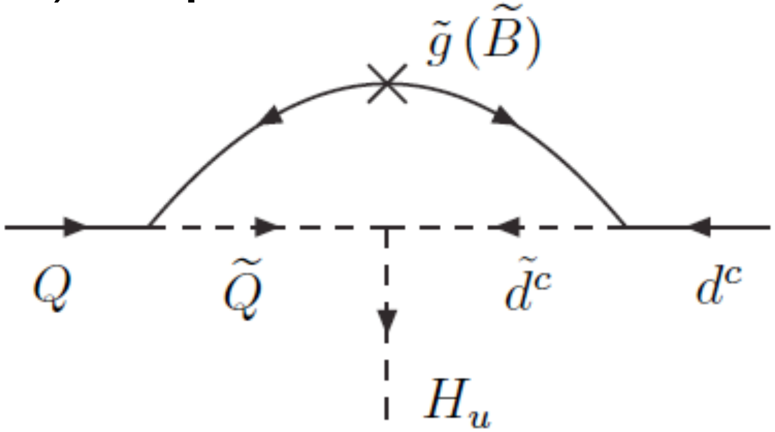
$\longrightarrow$ generate a completely general THDM

$$\mathcal{L} \supset -y_u u^c H_u Q_L - y_d d^c H_d Q_L - y'_u u^c H_d^\dagger Q_L - y'_d d^c H_u^\dagger Q_L$$

so, therefore $\quad m_d = y_d v_d + y'_d v_u$

more Uplifted SUSY

Example: gluino (or bino) loop



$$(y'_d)_F = -\frac{y_d}{3\pi} e^{i(\theta_g-\theta_\mu)} \frac{2|\mu|}{M_{\tilde{d}}} \left[\alpha_s F\left(\frac{M_{\tilde{g}}}{M_{\tilde{Q}}}, \frac{M_{\tilde{d}}}{M_{\tilde{Q}}}\right) + \frac{\alpha e^{i(\theta_B-\theta_g)}}{24 c_W^2} F\left(\frac{M_{\tilde{B}}}{M_{\tilde{Q}}}, \frac{M_{\tilde{d}}}{M_{\tilde{Q}}}\right)\right]$$

$$F(x,y) = \frac{2xy}{x^2-y^2}\left(\frac{y^2\ln y}{1-y^2} - \frac{x^2 \ln x}{1-x^2}\right)$$

effective coupling y'_d

- proportional to y_d
- knows about superpartner spectrum
- knows about complex SUSY parameters

+ additional diagrams from Higgsino loops or involving A-terms

more Uplifted SUSY

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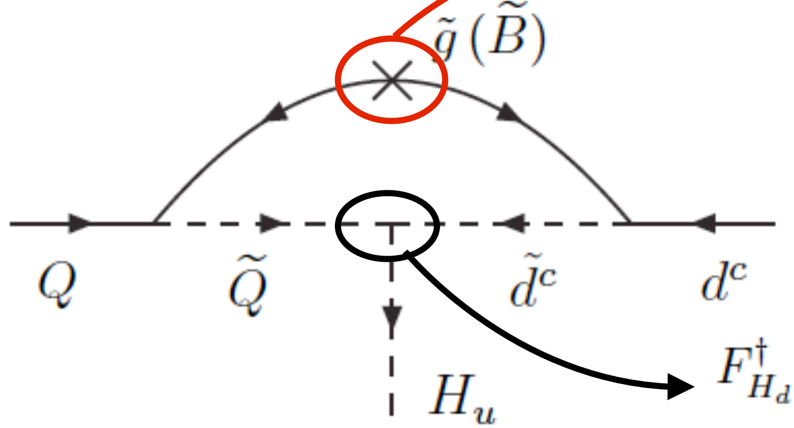
SUSY breaking



$F^\dagger_{H_d} = y_d\,\tilde{d}^c\widetilde{Q} + y_\ell\,\tilde{e}^c\widetilde{L} - \mu H_u$

$$(y'_d)_F = -\frac{y_d}{3\pi} e^{i(\theta_g - \theta_\mu)} \frac{2|\mu|}{M_{\tilde{d}}} \left[\alpha_s F\left(\frac{M_{\tilde{g}}}{M_{\tilde{Q}}}, \frac{M_{\tilde{d}}}{M_{\tilde{Q}}}\right) + \frac{\alpha e^{i(\theta_B - \theta_g)}}{24 c_W^2} F\left(\frac{M_{\tilde{B}}}{M_{\tilde{Q}}}, \frac{M_{\tilde{d}}}{M_{\tilde{Q}}}\right) \right]$$

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- knows about complex SUSY parameters

+ additional diagrams from Higgsino loops or involving A-terms

more Uplifted SUSY

if sfermion spectrum is NOT degenerate, ex.) $M_{\tilde{Q},3} \neq M_{\tilde{Q},1}$

$$F\left(\frac{M_{\tilde{g}}}{M_{\tilde{Q},3}}, \frac{M_{\tilde{d},1}}{M_{\tilde{Q},3}}\right) \neq F\left(\frac{M_{\tilde{g}}}{M_{\tilde{Q},1}}, \frac{M_{\tilde{d},1}}{M_{\tilde{Q},1}}\right) \quad \text{so} \quad \frac{y'_{d,13}}{y_{d,13}} \neq \frac{y'_{d,11}}{y_{d,11}}$$

mass term: $y_d v_d + y'_d v_u$

Yukawa: y_d

are not simultaneously diagonalizable: FCNC!

great, but y'_d is loop suppressed, so one expects these effect to be negligible...

Uplift!

what if : $\frac{v_u}{v_d} \sim 200$??

$$m_b = (y_b\ v_d + y_b'\ v_u)$$

- large $\frac{v_u}{v_d}$ overcomes the loop factor
- $y_d' v_u$ becomes dominant contribution to mass
- big y_b (also y_τ) needed to get right m_b, m_τ

$$y_\tau\,, y_b \sim \mathcal{O}(1) \qquad y_{d,s} = y_b \frac{m_{d,s}}{m_b}\text{, etc.}$$

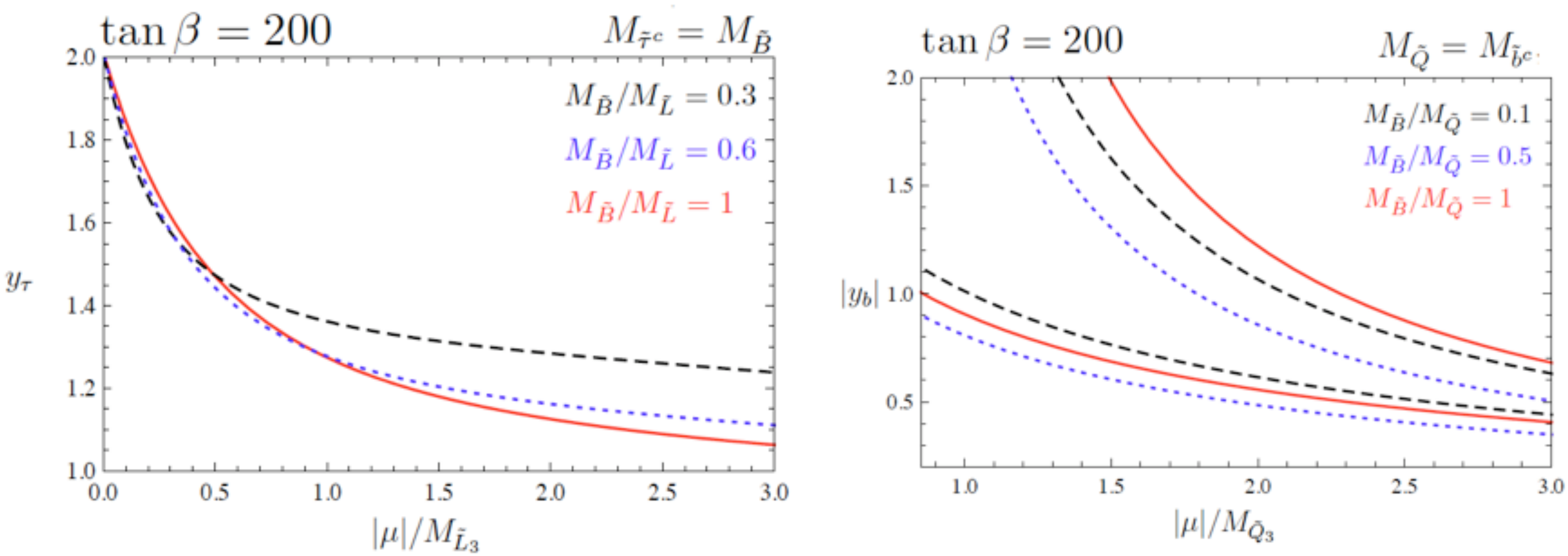
This is the \`uplifted region'

(Dobrescu, Fox 1001.3147)

Uplift! : How did we get here?

(see 1001.3147)

- B_μ term is zero at tree level
- $(m^2_{H_u} + |\mu|^2) < 0 \quad , (m^2_{H_d} + |\mu|^2) > 0$
- only the up-type Higgs gets a vev. $v_u/v_d = \infty$!
- loop effects generate B_μ , small $v_d \longrightarrow v_u/v_d \gg 1$
- $y_b \;,\; y_\tau \sim \mathcal{O}(1)$ but certainly perturbative



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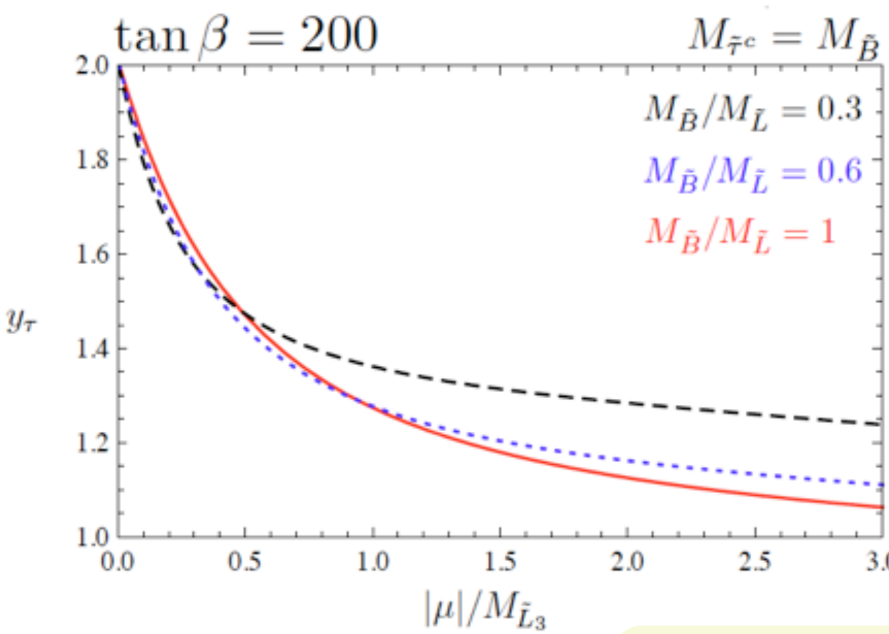
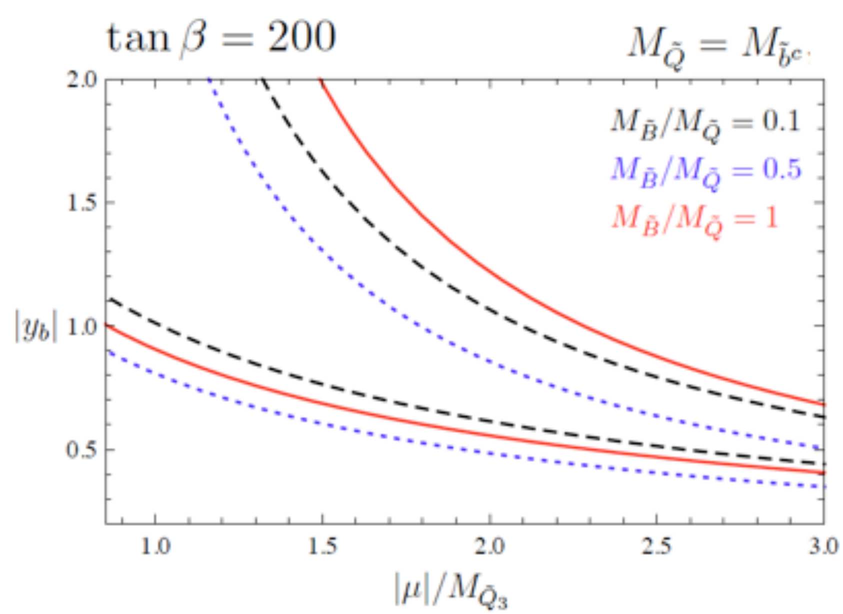




careful, $v_u/v_d = \tan\beta$ is a confusing parameter!

Uplifted SUSY + flavor

for $\frac{v_u}{v_d} \gg 1$ heavy neutral Higgs (H^0/A^0) lie in the H_d doublet

$$-y_d \; d^c \; H_d^0 \; d_L$$

Diagonalizing the mass term, you get off-diagonal entries in $y_{d,ij}$

$$y_{bs} = y_b \; V_{ts} \; \xi \qquad y_{sb} = \frac{m_s}{m_b} y_{bs}$$

order 1

order 1, complex, sensitive to splitting of sfermions

off-diagonal entries are big $(\mathcal{O}(V_{CKM}))$ and carry new, potentially large phases

right in the range needed to have an effect on B_s for $m_A \sim$ TeV

Uplifted SUSY + flavor

- effects in B_d system suppressed by m_d/m_s

- flavor changing couplings vanish when sfermions are degenerate, so if $M_{\tilde{Q}_1} \cong M_{\tilde{Q}_2} \neq M_{\tilde{Q}_3}$

$$M_{\tilde{d}_1} \cong M_{\tilde{d}_2} \neq M_{\tilde{d}_3}$$

$\Rightarrow$ no flavor-violation in the Kaon system

Starting from degenerate sfermion masses at a high scale, Yukawa couplings in RGEs will automatically generate the desired splitting

$$y_b \sim 1\,,\, y_{s,d} = y_b \frac{m_{s,d}}{m_b} \ll 1 \longrightarrow M_{\tilde{Q},3} < M_{\tilde{Q},1,2}$$

(Dobrescu, Fox, Martin work in progress)

What else can Uplifted SUSY do for you?

- interesting effects in another B-system anomaly
- distinct collider signals

Uplifted SUSY + flavor

other interesting effects: $B^{\pm} \to \tau^{\pm}\nu$

SM: $B(B^- \to \tau\nu)_{\rm SM} = (0.84 \pm 0.11) \times 10^{-4}$ **(UTfit: 0908.3470)**

Belle + BaBar: $B(B^- \to \tau\nu) = (1.73 \pm 0.34) \times 10^{-4}$

- in the MSSM (or other `type-2' THDM):

$$\frac{B(B^- \to \tau\nu)}{B(B^- \to \tau\nu)_{SM}} = \left[1 - \tan^2\beta \frac{M_B^2}{M_{H^\pm}^2}\right]^2$$

hard to manage an enhancement without throwing off other observables

- in `uplifted SUSY':

$$\frac{B(B^- \to \tau\nu)}{B(B^- \to \tau\nu)_{\rm SM}} = \left[1 - \left(\frac{y_b}{y_b v_d + y_b' v_u}\right)\left(\frac{y_\tau}{y_\tau v_d + y_\tau' v_u}\right)\frac{M_B^2}{M_{H^-}^2}\right]^2$$

we can have a relative (-) between y_b and y_b' :

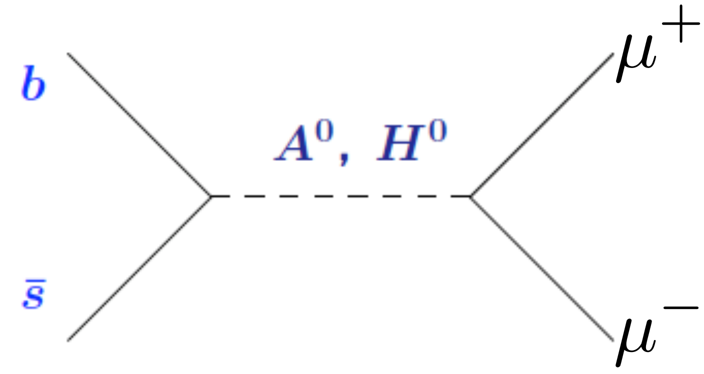
enhances $B^{\pm} \to \tau^{\pm}\nu$

Uplifted SUSY + flavor

more effects:

- $B_s^0 \to \mu^+\mu^-$

  affected by same process:

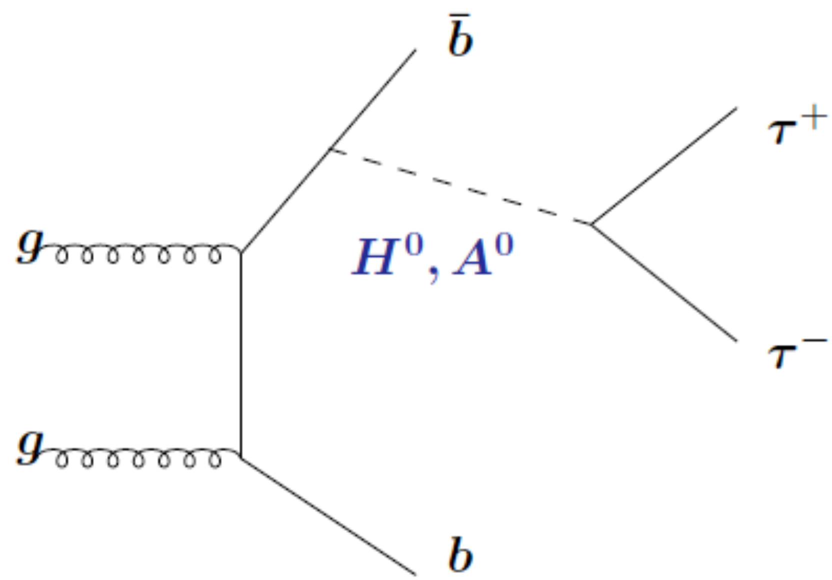


- altered collider signatures

  large y_τ

  large BR (~30 - 80%) for heavy Higgses (H/A) to $\tau^+\tau^-$

  (vs. 10% in usual MSSM)



Conclusions

- D0 like-sign dimuon asymmetry, interpreted as B oscillations means there must be BSM physics

- it's tricky to work in new physics to explain excess without messing up existing flavor constraints

- One possibility: new physics in phase of M^s_{12} -- NP must be large with large phase. In this case, should see an effect in $S_{\psi\varphi}$

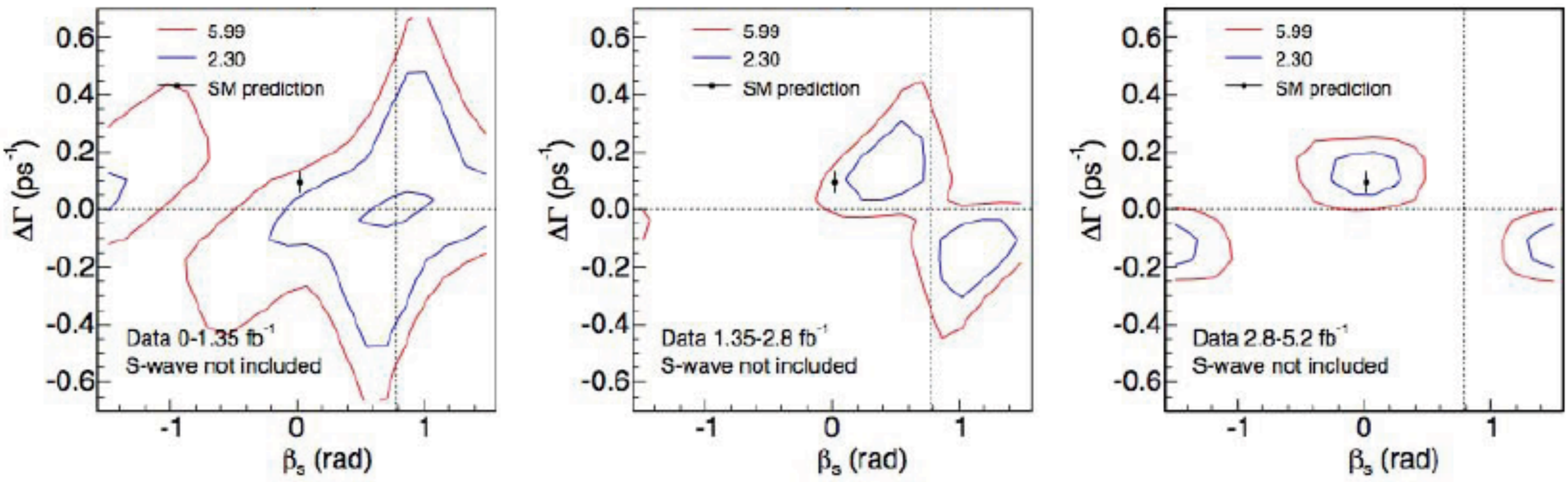
'Uplifted SUSY' region is one scenario with the right properties to explain excess

- FCNC through H/A exchange
- couplings sensitive to complex SUSY parameters
- assuming $M_{\tilde{Q}_3} \neq M_{\tilde{Q}_1} \simeq M_{\tilde{Q}_2}$

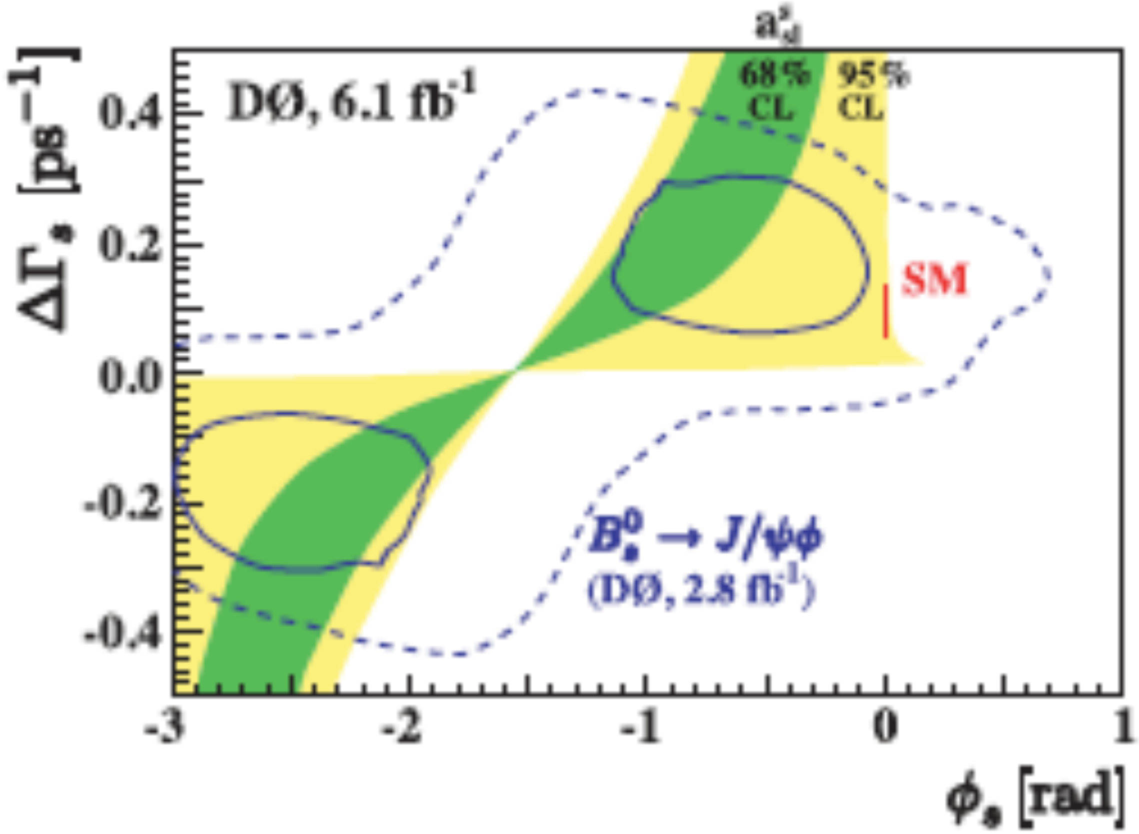
  effects in $B^0_s \; > \; B^0_d \; \gg \; K^0$
- other B-system/collider signatures soon

EXTRAS

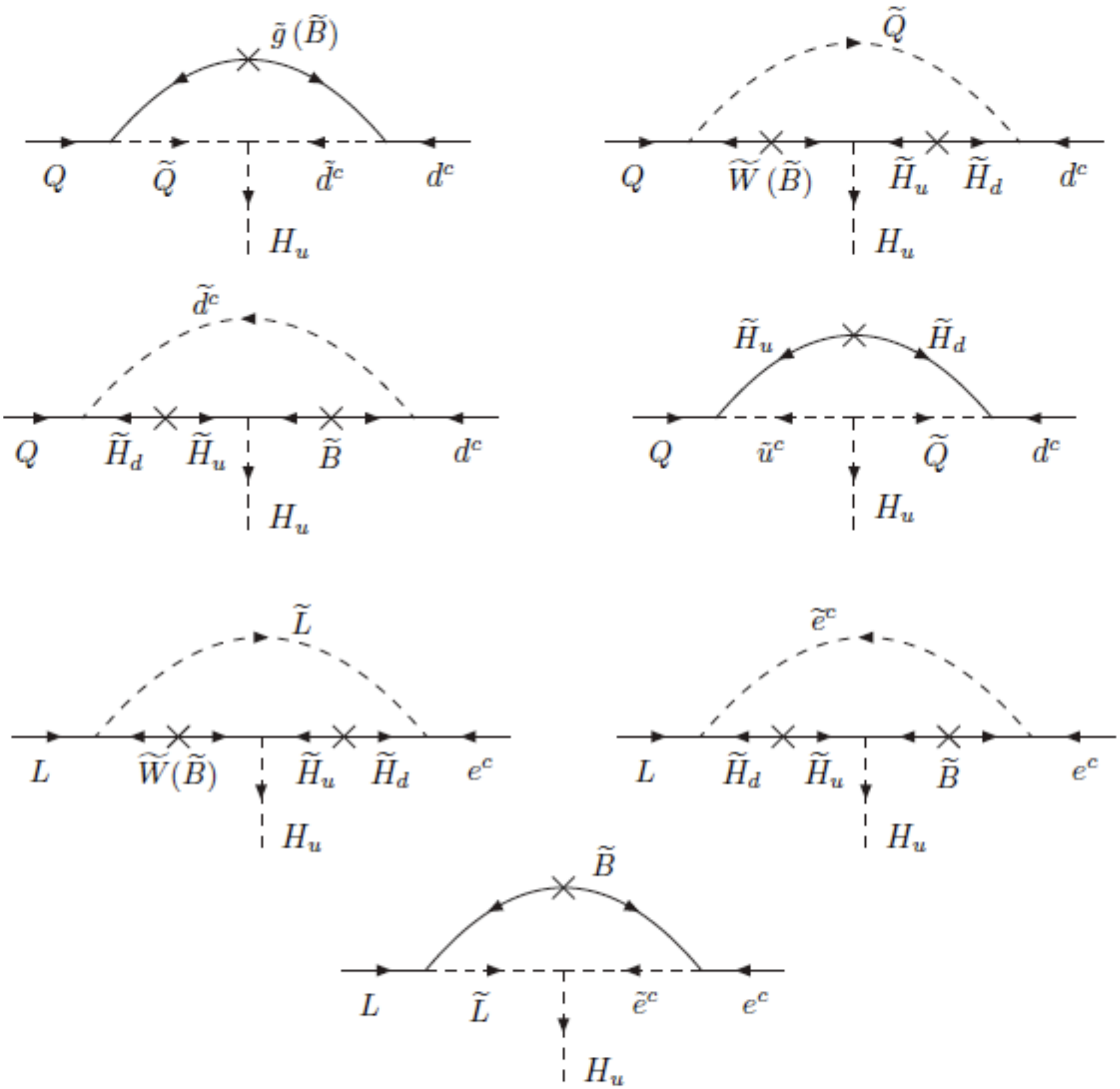
Latest CDF $S_{\psi\phi}$



Combining $S_{\psi\varphi}$ and a^s_{SL}



more Uplifted SUSY

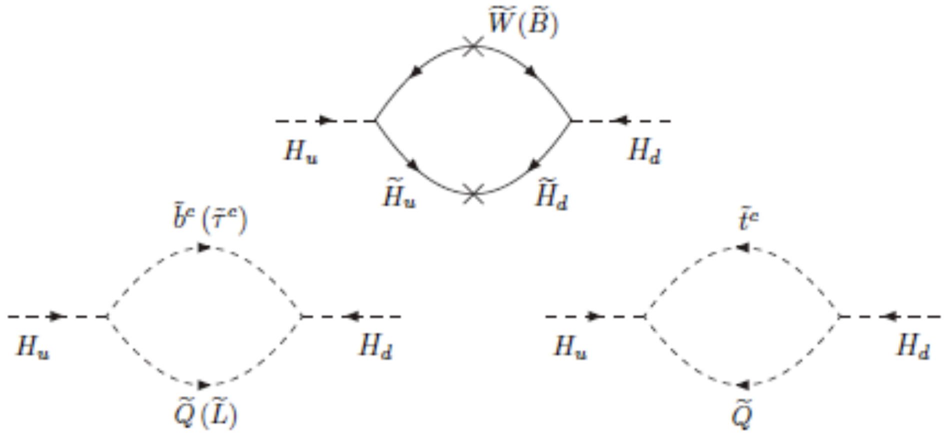


down-type quarks

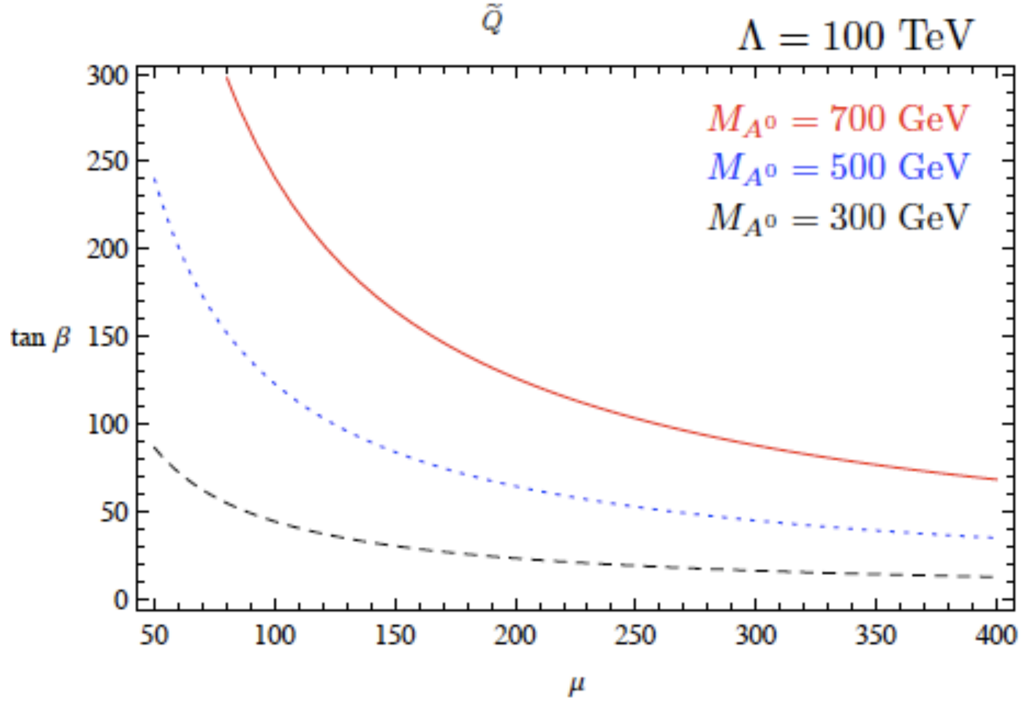
leptons

more Uplifted SUSY

Once SUSY is broken B_μ generated at one loop



Log divergent



(slide by P. Fox)